Data Analysis of Cosmic Microwave Background (CMB) Experiments

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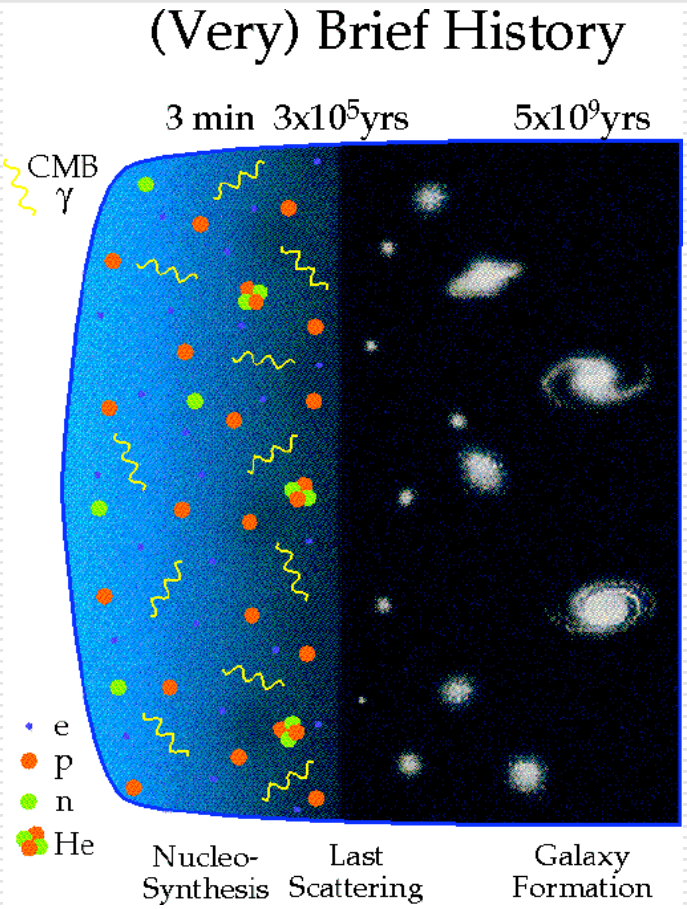
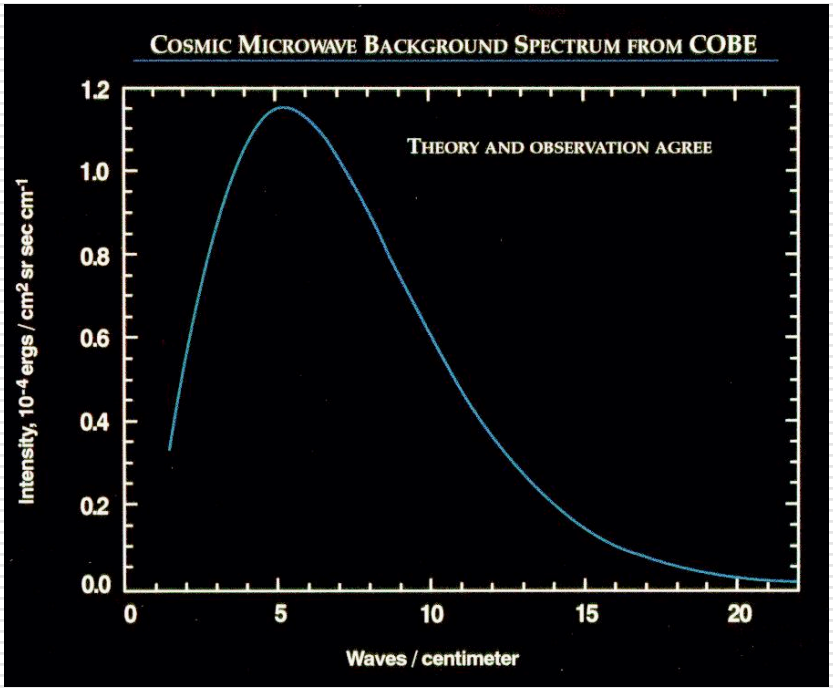
What is the CMB?

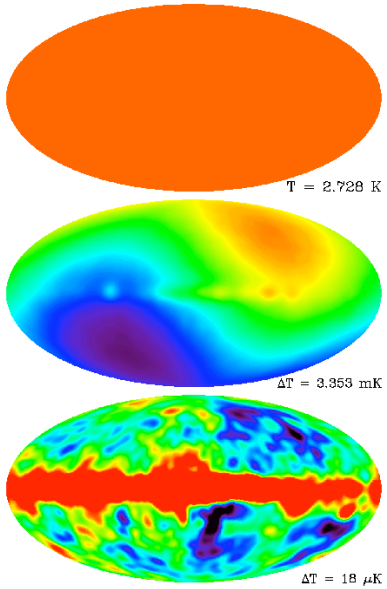
- Last interacted with matter at ~300,000 years after the Big Bang.
- Existence is a direct prediction of Big Band model.
- First detected by Wilson & Penzias (Nobel Prize 1965)
- 1% T.V. 'fuzz' is CMB.



Observing the CMB – COBE (1992)

2.73 Kelvin Blackbody





dipole

anisotropies

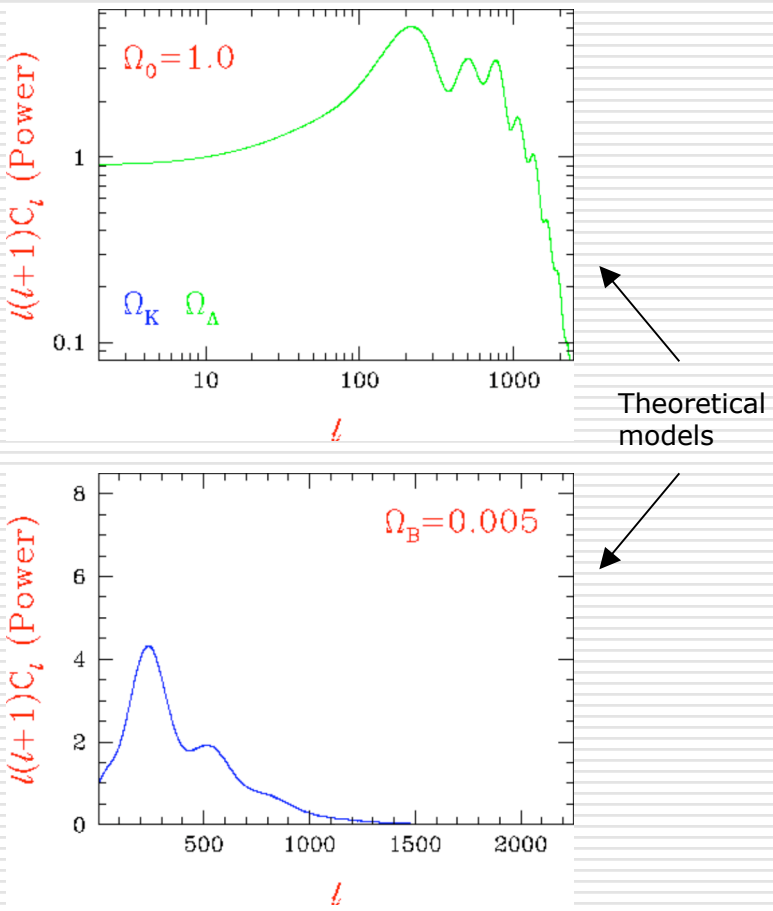
Perfect blackbody -> radiation in thermal equilibrium

CMB Power Spectrum

- Encodes statistical information of anisotropies.
- Provides excellent method for comparing theory and data.

$$\Delta T(\theta,\phi) = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi)$$

$$\langle a_{lm} a_{l'm'} \rangle = C_l \delta_{mm'} \delta_{ll'}$$



http://background.uchicago.edu/~whu/

MAXIMA

- Balloon-borne experiment to measure CMB anisotropies at high resolution.

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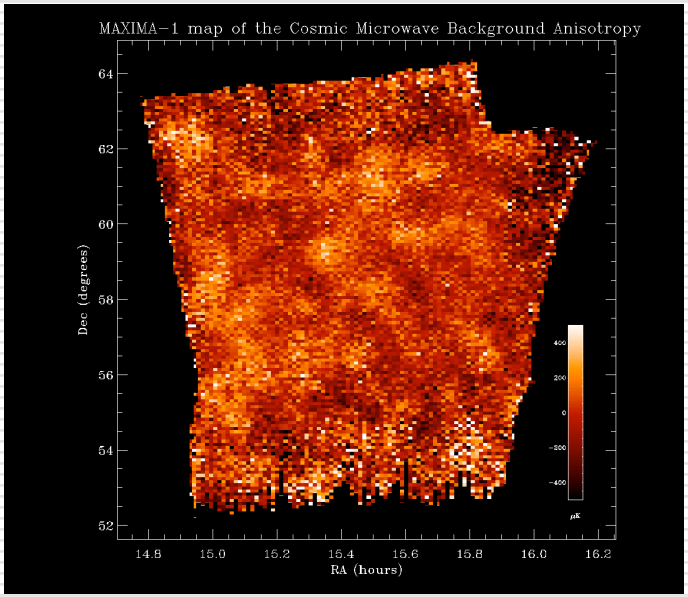
Copernicus Astronomical Center[9]



MAXIMA-I picture of the CMB (1998)

Why do we need supercomputers?

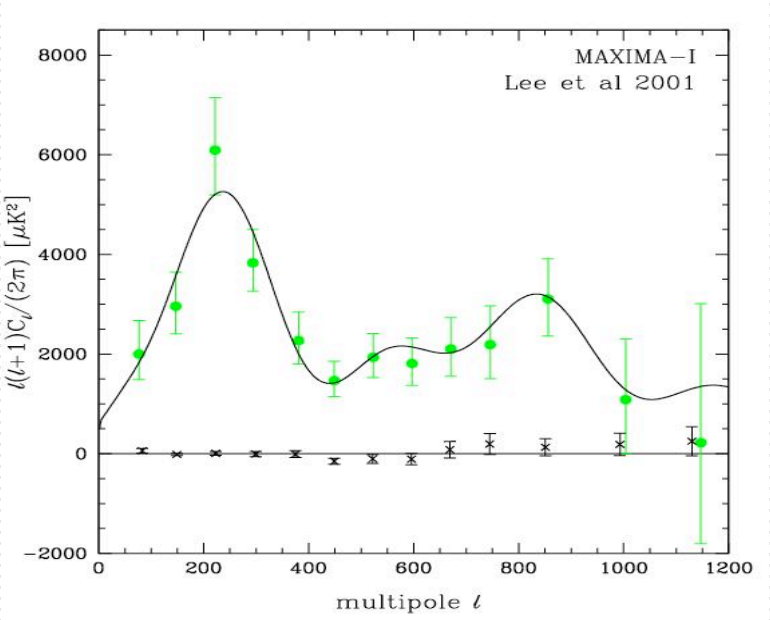
- *d* is the pixelized anisotropy map, which has a multivariate Gaussian distribution with covariance matrix *M*.
- Maximize the likelihood *L* as a function of C_l.

$$-2\ln L = N_P \ln|M| + d^T M^{-1} d$$

$$M_{ij} = \sum_l \frac{2l+1}{4\pi} C_l P_l(\cos\theta_{ij})$$

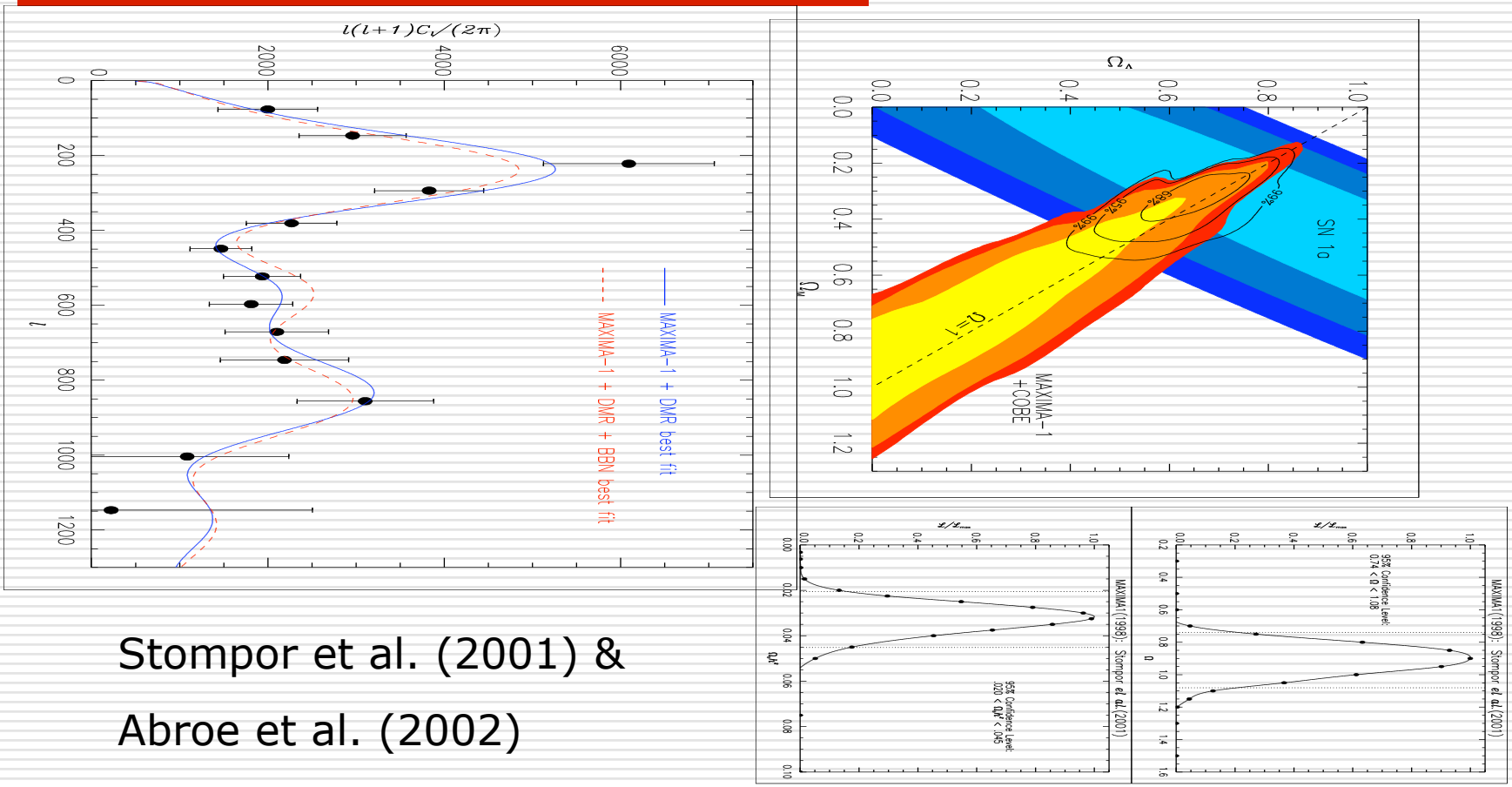
- M_{ij} is a large dense matrix *(*N_p by N_p where N_p ~ 90,000*).*
- Done with a Newton-Raphson technique for finding the zero derivative (matrix inversion and matrix-matrix multiplications).
- Described by Bond, Jaffe, Knox (1998), parallel implementation by Julian Borrill at NERSC (MADCAP).

MAXIMA-I power spectrum



- Highest resolution measurement of CMB anisotropy at the time.
- Computational resources are provided by NERSC and the Minnesota Supercomputing Institute (MSI).

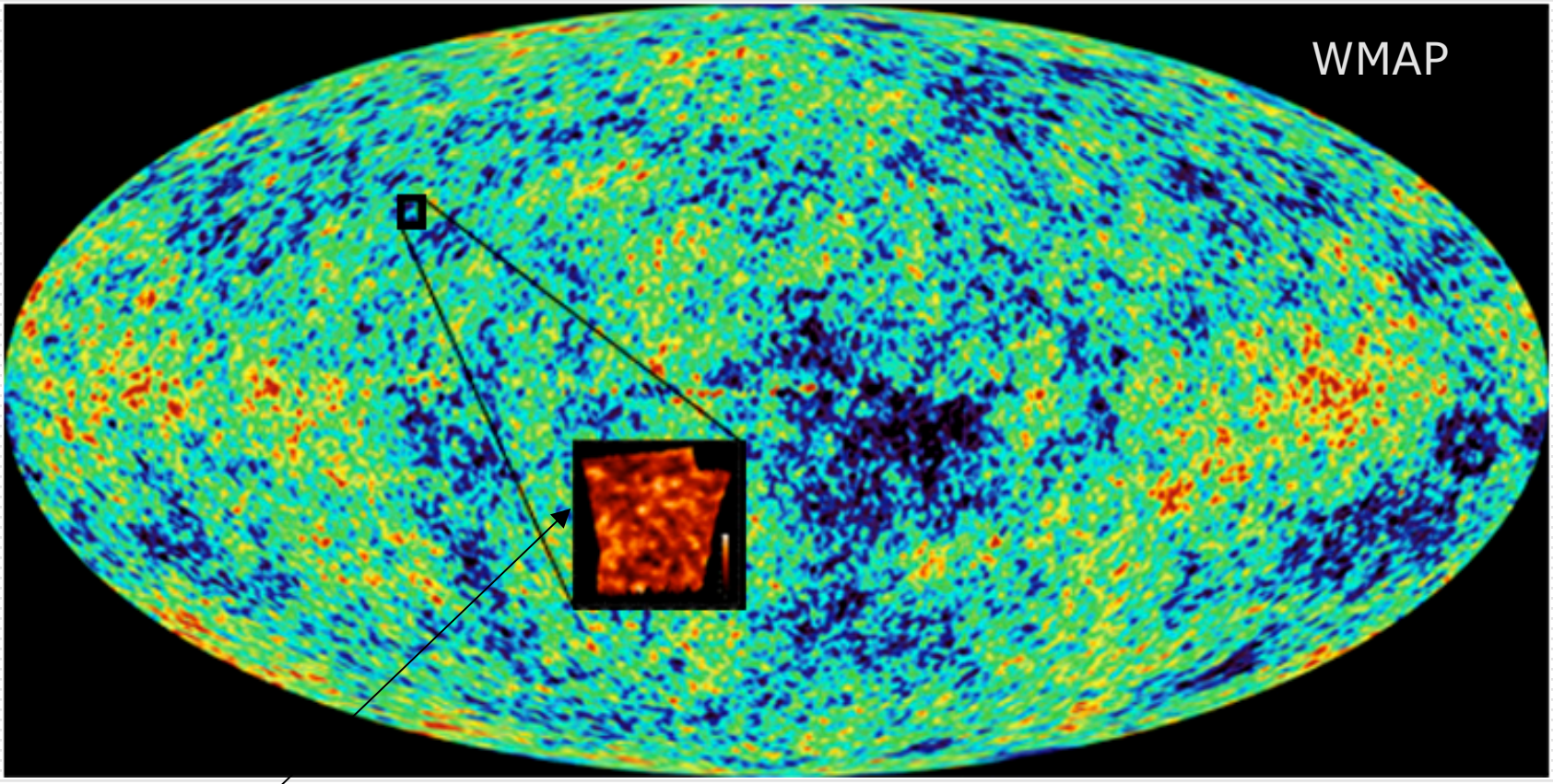
Cosmological Parameter Estimation



Stompor et al. (2001) &

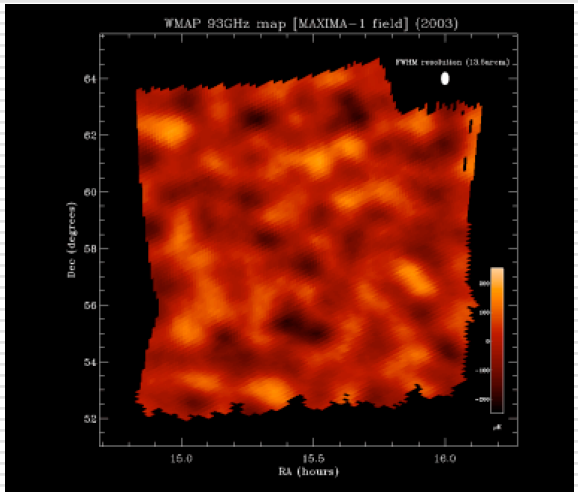
Abroe et al. (2002)

WMAP & MAXIMA

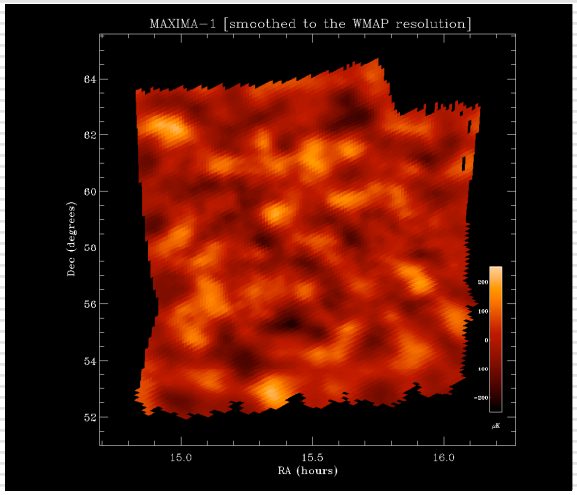


WMAP & MAXIMA (cont.)

WMAP



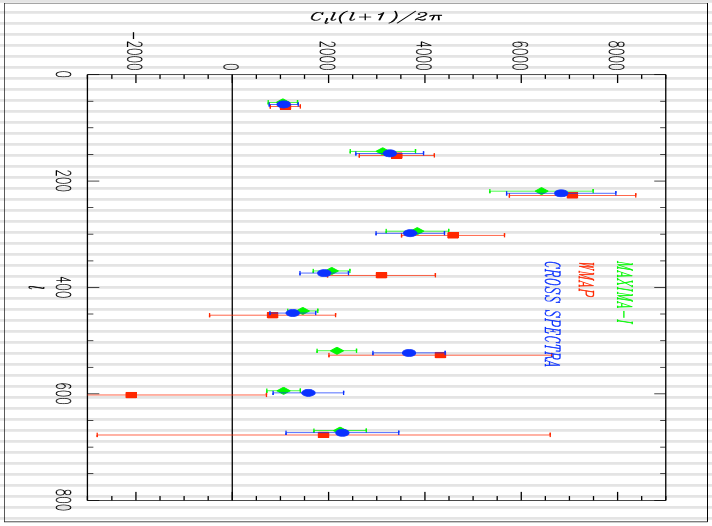
MAXIMA-I



Similar structure seen in both maps !!

Cross Spectrum

- Measures correlation between two maps on various angular scales.
- Computationally intensive.
- Similar algorithm for power spectrum -> generalized to include two temperature maps.

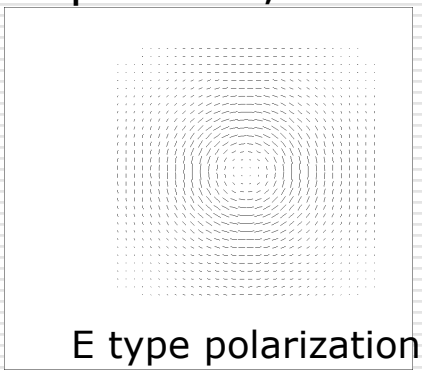


Positive cross spectrum -> positive correlation in maps.

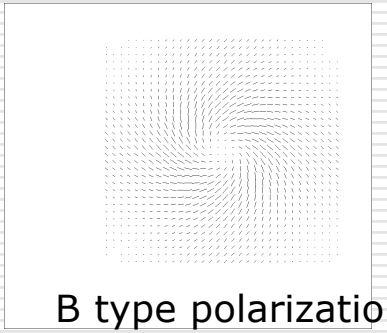
Abroe et al. (2003, in preparation)

CMB Polarization

- CMB photons are Thomson scattered off of free electrons -> induces linear polarization.
- The polarization signal is expected at ~10% of temperature signal (at several _K !!).
- Polarization can be described in terms of Stokes parameters: *I*, *Q*, and *U* (observables).
- These can be decomposed into curl free and divergence free components, called E and B by analogy to electromagnetism.



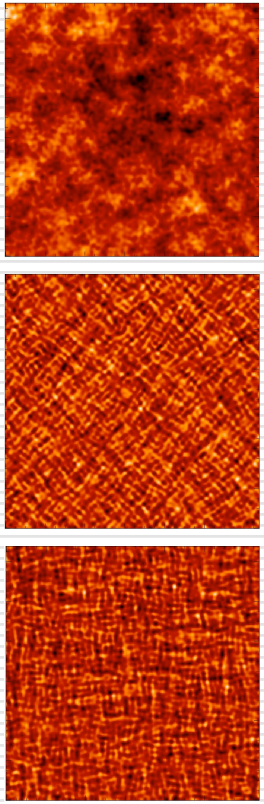
E type polarization



B type polarization

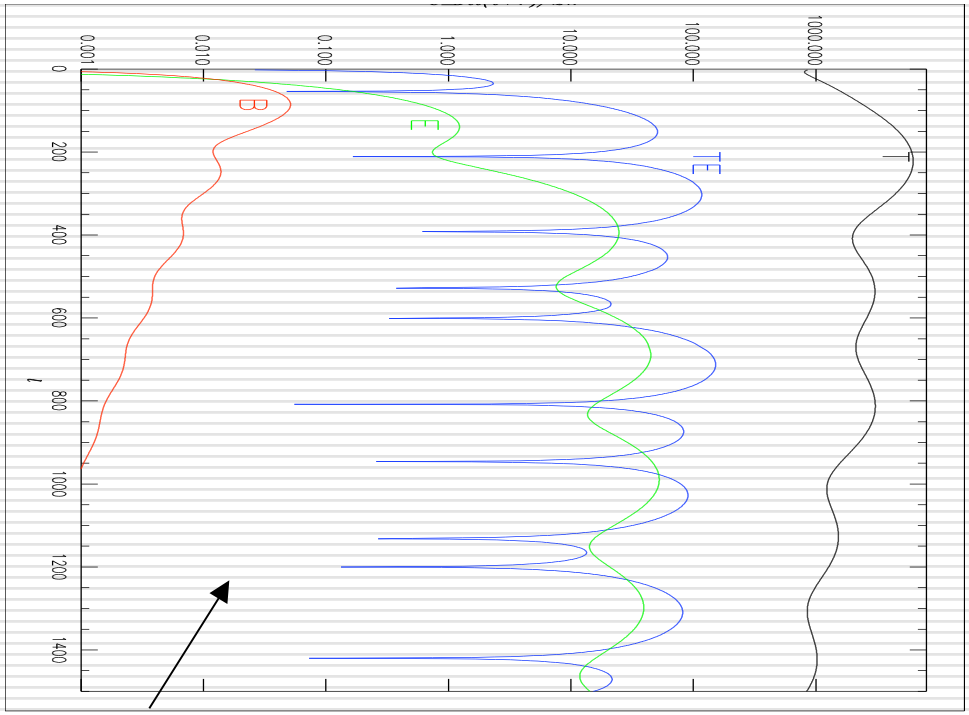
CMB Polarization (cont.)

Observables



(simulated maps)

Theoretical models



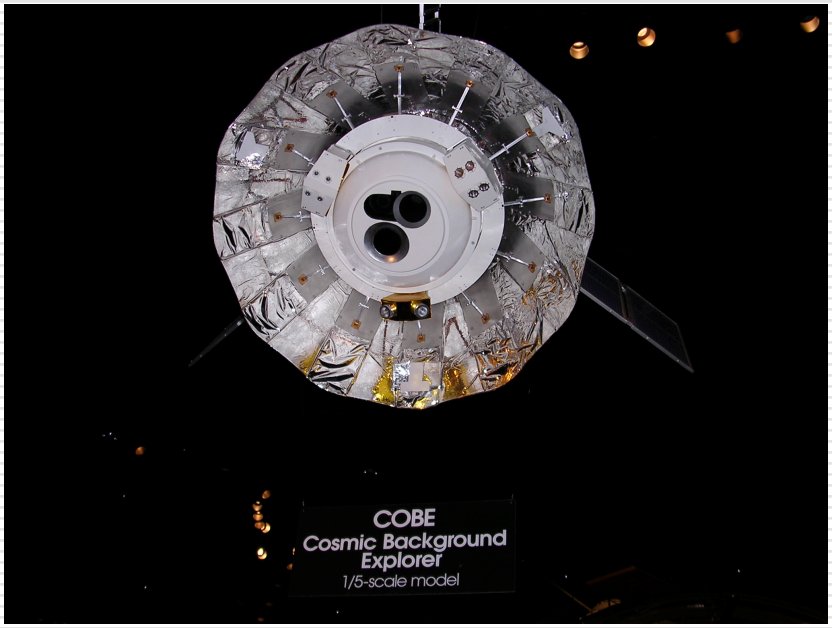
Induced only by primordial gravitational waves

MAXIPOL

- Balloon Borne experiment to measure the CMB polarization.
- Same instrumentation as Maxima, outfitted with polarizer.
- First flight, Fall 2002 -> telemetry failure.
- Successful Flight, Spring 2003. Data analysis in progress.

MAXIPOL-0 Launch (Fall 2002)

The Smithsonian thinks CMB is cool!!



1/5 scale COBE model

Boomerang Info